TECHNICAL AND ECONOMICAL STUDIES FOR METAL PRODUCTION BY PLASMA-STEELMAKING APPLICATION

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ABSTRACT

After the description of the principal plasma techniques for the metal making,we present the Limoges'University choice for iron making by an advanced technique in a power reactor. The technico-economical study of the cost of direct iron making by plasma is comparable to those obtained by conventional techniques.

1. INTRODUCTION

Many bibliographic studies /1/ to /6/ have been devoted in recent years to different types of plasma furnaces and their industrial applications and future prospects.

In this work, we propose first to describe briefly plasma furnaces used in extractive metallurgy, to present the Limoges reactor and the early results obtained for iron steelmaking and finally to propose an economical modelisation for the treatment of iron ore.

2. METALLURGICAL REACTORS

We will try to give a classification of the different categories of plasma furnaces used increasingly for metallurgical investigations. This analysis of it

classification is based on the residence time of the treated material generally fed as particle for which we can calculate the received energy by a semi-empirical expression. This relation, very complicated in its general form /7/ is simplified /8/ by assuming that the particles diameter d is constant and that the heat propagation in the particle is instantaneous:

$$E = \frac{6}{\rho d} \int_{0}^{t_s} \{h(T-T_p) + \sigma\varepsilon\,(T_o^4 - T_p^4)\}\,dt$$

where ρ is the specific mass of the particle, t_s the mean residence time of the particles in the plasma, h the convective exchange coefficient, T, T_p and T_o respectively plasma, particle and wall temperatures and ε the particle emissivity (the wall is supposed to be a black body).
Therefore, to obtain a maximum value of E one must :

- increase the residence time t_s
  the convective exchange coefficient h
  the wall temperature T_o
- decrease the particule diameter d.

However these different parameters are not independant and acting on one of them to increase the value of E modifies the others in the opposite direction. For example, to increase h one can increase the plasma flow velocity but doing so decreases the residence time t_s.
The classification (similar to that of BONET /8/) based on the residence time is given in Table 1.

Table 1 : Classification of Plasma Furnaces

t_s(S)	d(10^{-6}m)	T_p(K)	T_o (K)	Type
$\simeq 10^{-3}$	$\simeq$ 100	$\simeq 10^4$	Low	A
10^{-2} à 1	100	5.10^3	Low 2.10^3	B B
1 à 10^2	-	5.10^3	2.10^3	C

The C type may be further subdivised in two types : furnaces in which the feed material also acts as an electrode (heat transfer increase very appreciably) or not.

2.1. A type reactor :

The particles of ore are injected into the plasma core, the residence time is short but the convective exchange coefficient is high. Some furnaces use the magnetohydrodynamic effect (first observed by MAEKER /9/) : a low pressure is created near the cathode tip into which the surrounding gas and the particles are rapidly entrained. In the Noranda reactor /10/ (table 2) the arc is struck between a shielded cathode and an anode placed at the bottom of a crucible. Its electric power is about 100 kW, and it is used for molybdenite desulfurisation. In other furnaces, the particles areinjected directly into a homogeneous plasma formed by three plasma jets produced with A.C. , a rather different system utilises high power generators using water cooled copper ring electrodes in which the plasma is stabilised by the combination of high velocity gas purged between the electrodes and a magnetic field. The use of this device by Westinghouse /11/ with a few MW power has been studied for chromite and manganese ore treatment (Table 2).

2.2. B type reactor :

The particles residence time is increased by two methods:

a- counter current particles injection, for example the 25 kW A.C. furnace of the Toronto University, with graphite electrodes and hot wall is used for chromite ore reduction /12/,and the Odeillo furnace where the illmenite powder is fluidized and treated by a D.C. plasma generator fixed in the bottom of fluidized column /13/ (Table 2).

b- increased volume of plasma using an Expanding precessive plasma reactor as the one of Tetronics/14/. The expansion is realised by the precessive movement of the cathode in front of a toroidal anode . Presently working at 300 kW power level for iron ore reduction (Table 2) it is expected to be scaled up to 1.4 MW by Foster Wheeler.

2.3. C Type reactor :

The material treatment starts in the dispersed form and finishes on the wall where it forms a liquid film. As we have already mentioned we will separate this furnace intotwo groups, in the first onethe falling film is not used as an electrode and in the second (where the film is used as electrode) the heat transfer is enhanced:

- in the first group we have the rotating drum plasma furnaces.

The NPL /15/ vertical rotating drum furnace is fired by two plasma generators, with power transfer. The injected particles are centrifugated onto the wall where they melt and form the flowing film.
Its total power is about 120 kW , and it has been used for tin ore treatment (Table 2).
- The second group concerns vertical static reactors.
The injected particles stick on the wall and melt but the falling film is used as the anode, thus enhancing the efficiency of the heat tranfer /16/ to the reactants and reducing the heat losses to the anode . In Bethlehem Steel Corporation /17/ and /18/ and Limoges University /19/, oneMW reactor has been tested for the reduction of iron ore with hydro gen and methane and in Bethlehem a 500 kW furnace has been tested for the production of ferrovanadium alloys using carbon as reducing agent. (Table 2)

3. LIMOGES PLASMA REACTOR

In collaboration with EDF, CEA, PUK and the Industrial Office, we have developed in Limoges a high power plasma reactor (up to 1 MW). The facilities have been developed to be used for different operations in plasma chemistry at a high power level. The power supply can be connected to work in various combinations 0-300 A.and 0-2400 V, 0-600 A. and 0-1200 V, and 0-1200 A and 0-600 V. The cooling system operates using deionised water in closed circuit with two heat exchangers and the plasma gas flow rate can go up to 200 N m^3/h. For extractive metallurgy operation the plasmafurnace is used with hydrogen and natural gas. Figure 1 shows the general arrangement of this installation.

3.1. Furnace description

The plasma reactor is formed of three elements :

-a) The reaction chamber: The chamber consists of a stack of identical reactor cells. This strusture is closed by two webs placed downstream and upstream of the chamber . Every reactor cell or stage is surrounded by a metallic water jacket. Double novel electrical insulation is assured between the stages. An insulating ring separates mechanically the water jacket of the reactor cells and allows the passing of probes and the injection of gas or powder transported by a pneumatic system. One, two or all of the cells may be connected to the positive pole of the electrical supply and act as anodes.

-b) The cathode : The cathode is the only moving part of the system and acts like a plunging core in the reaction chamber. It is a water-cooled tungsten tip cathode with two independent gas flows around it (interior and exterior) separated by a stainless steel shield which is insulated from the anode by a zirconia, plasma sprayed, deposit. The cathode is also supplied with a central gas injection device.

-c) The crucible : The crucible used to collect the reaction products has a magnesia lining and is heated directly by the plasma gas. A vent-hole is used to evacuate gas to the burner.

The arc is ignited between the cathode and the last reactor cell (this ignition is done by an auxilliary electrode) and is then expansed by drawing up the cathode. The cathode tip can be placed in front of the gas or powder injection inlets.

Theparticules are treated in the plasma jet as well as in the falling liquid film formed on the wall of the reactor, and in the crucible.

The gas flows out to a burner or a prereduction device and then to a washing-cooling tower before being rejected to atmosphere after passing through cyclone for dust removal

In the case of the reduction of iron ore, typical results obtained are as follows:

Reducing gas : hydrogen
Initial product : hematite (1 to 100 µm)
Product on the liquid film : Fe total 98,2 % } η = 91 %
Fe metal 88,3 %
(11% FeO)
Crucible : iron
Wall of the crucible : Metallic iron shells formed by condensation.

A statistically planned series of experiments allows us to understand better the working characteristics of the metallurgical reactor which are governed qualitatively and quantitatively by the characteristics of the gas stream.

Qualitatively the gas having the highest arc voltage determines the arc voltage of the gas mixture.

Quantitatively the gas flow and the position of injection predominate .

The following figures illustrate this:

figure 2 : the heat losses in the cooling system and the heat efficiency of the reactor increasing with the power,
figure 3 : the evolution of the gas enthalpy (MJ/kg) with the rate of hydrogen to constant argon flow (80 Nl/min) ; the dashed-line represent the theoretical enthalpy calculated for an equilibrium Ar + H_2 plasma.
figure 4 : the evolution of arc characteristic with the total gas flow.

4. ECONOMICAL MODELISATION

The results of Bethlehem Steel /17/, Foster Wheeler /14/ as well as those of Limoges /19/ demonstrate the great advantage of different types of plasma reactor to convert iron ores directly to virtually pure molten iron in a single step plasma reactor process. We propose to prove the economical advantage of this plasma process compared with classical processes, especially for casting applications.
To establish an economic balance for a plasma unit, we have calculated the cost of each part of the unit. Our calculations are based on one ton of product from iron ore containing 60% iron. According to the published results of Bethlehem Steel /17/ and confirmed by our first results at Limoges, the minimum energy consumption is about 2,65 MW/Ton of iron product. This minimum is obtained for a ratio of hydrogen to methane flow of 2 to 2.5 /20/ . We carry out /21/ estimations based on the costs evaluated in 1978 and summarised in table 3.

	the unit-price	the necessary quantity	cost
ore containing 60% iron	100,00 F/t	1,67 t	167 F
grinding	15,00 F/t	1,67 t	25 F
gas			
- methane	0,29 F/m^3	333,00 m^3	97 F
- hydrogen	0,131 F/m^3	667,00 m^3	87 F
energy	present MWh 150F nuclear MWh 100F	2,645	397 F or 265 F(nucl)
manpower			60 F
investment depreciation fixed cost			400 F

Table 3 - Estimations of Costs for 1 ton of ore treated by plasma

The total cost price will be, according to our evaluation, about 1233 Fr./t based on the present energy cost, and about 1101 Fr./t on the hypothesis of the utilisation of electricity from nuclear sources (as EDF evaluate in 1977 the cost of this electricity in 1985).
A comparison of steel cost price, based on the available data, for the following different processes :

- Blast furnace + converter
- Direct reduction furnace + Electric arc furnace
- Plasma arc reactor

is presented on figure 5.
The ordinate values may vary with the industrial emplacement, however the figures show that the plasma process is viable in the classical process producting molten steel in the foundery.
However,in spite of the market constraints , on a long-term perspective, doing the equilibration of the price of raw materials so that the price of the molten steel obtained remains about the same for all processes for an equal product quality, we observe that two elements inflence the economical variation at short-term and thus the utilisation of the plasma process :

-nuclear power-station development allows a decrease in the cost of the electrical energy

-the optimisation of the existent process, allowing the reduction of the energy consumption and necessary gas. Indeed, as we showed previously, the thermal and therefore energetical efficiency increases with power (figure 2), so that an optimisation of the installation dimensions is possible. Furthermore the exit gas has a considerable residual enthalpy (evaluated at 28,5 % of the reactor received energy), and a temperature of about 2500°K, thus allowing an improved efficiency by the use of recuperation .
Finally we observe, from the gas composition analysis at the exit of the reactor that the residual reductant capacity is of the order of 70 %. This shows the necessity for the coupling of an ore prereduction plant utilising the plasma furnace gases to the plasma plant.

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METAL ore	Society or Laboratory	Power	Treatment Process	Energy Consumption	Obtained Product
MOLYBDENUM molybdenite	Noranda	100 kW	pyrolysis	30 to 60kWh/kg	Desulfurisation up to 97%
FERROCHROMIUM chromite :20 to 43% of Cr	Westinghouse	1 MW	low velocity hydrogen plasma reduction	non published results	
FERROCHROMIUM chromite : 38 to 55% of Cr_2O_3	University of Toronto	25 kW	Coal reduction	10 to 30kWh/kg	C Si S P 7 6 .01 .04
ilménite	CNRS ODEILLO	40 kW	pyrolisis	work in progress	
IRON Hematite	Foster Wheeler	1.4MW	coal reduction in A-N_2 plasma	2.5 to 4kWh/kg	S P C Si .01 .005 .01 .01
TIN ore at 3.4% of Sn	N.P.L.	120kW	SnO evaporation by N_2 plasma	160kWh/kg Sn	SnO
IRON Magnetite, hematite	Bethlehem Steel	1 MW	Reduction by H_2 + CH_4 liquid film	3 to 5 kWh/kg	S P Si C .005.001.01.006
FERROVANADIUM V_2O_3 + Fe_2O_3	Bethlehem Steel	500kW	Reduction by C or H_2+CH_4 liquid film	10 to 80kWh/kg	V Fe C 42 52.9 3.1 O_2 Si S 0.95 0.32 0.44

Table 2 : Different types of metallurgical plasma furnaces

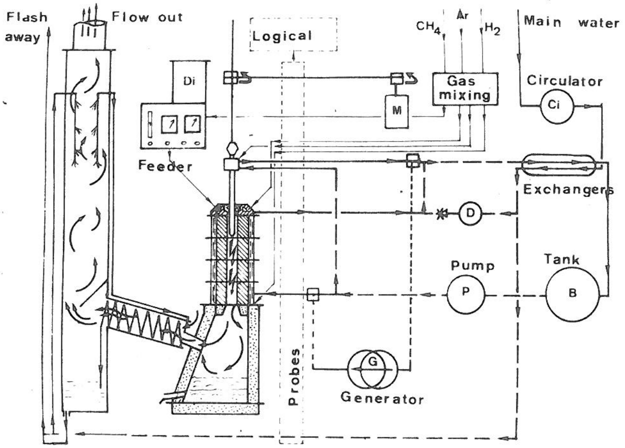
Flash away
Flow out
Logical
CH4
Ar
H2
Main water
Di
Gas mixing
M
Circulator
Ci
Feeder
Exchangers
D
Pump
P
Tank
B
G
Generator
Probes

Fig. 1

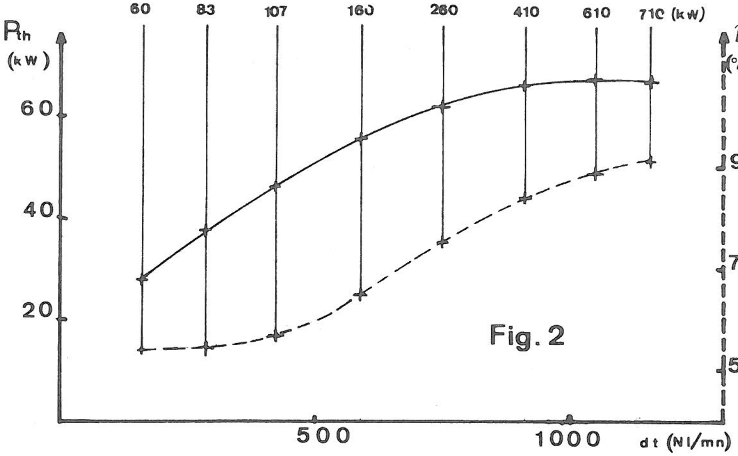
Pth (kW)
60
40
20
60
83
107
160
260
410
610
710 (kW)
η (%)
90
70
50
500
1000
dt (Nl/mn)

Fig. 2

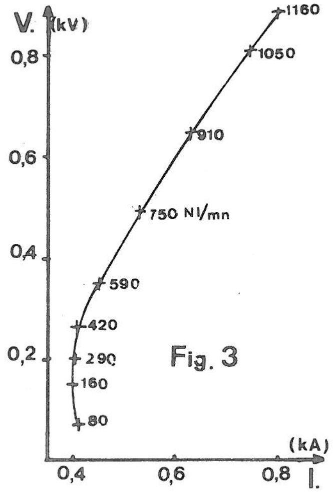

Fig. 3

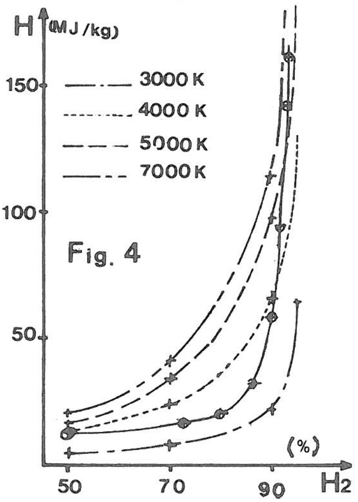

Fig. 4

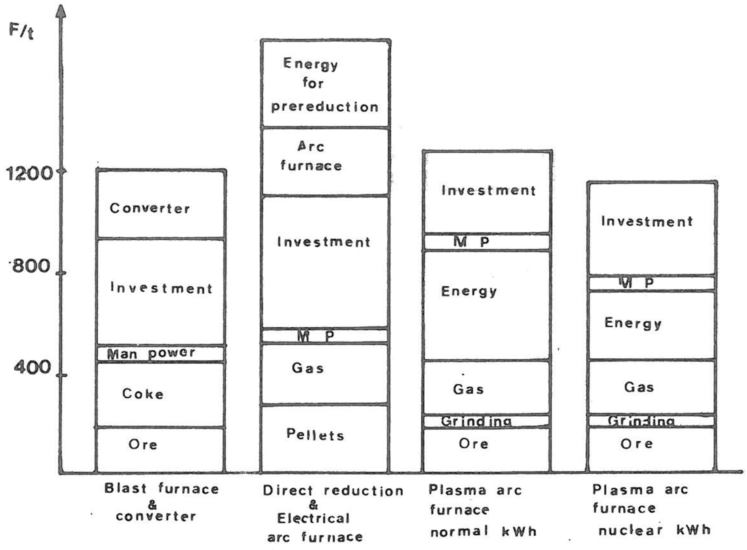

Fig. 5 Economic comparison of processes steelmaking